

NUCLEAR PHYSICS INSTITUTE at  
TOMSK POLYTECHNIC UNIVERSITY

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**HIGH POWER MICROSECOND MICROWAVE  
GENERATOR IN VIRCATOR TRIODE**

*Final Report*

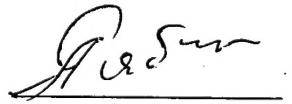
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13. ABSTRACT (Maximum 200 words)  This report results from a contract tasking Tomsk Polytechnical University as follows: The contractor will perform two primary tasks as described in his proposal; 1) design, construct and fabricate the vircator triode. The voltage source, multipoint cathode and mesh anode shall be optimized to provide long pulse and high efficiency operation. Frequency chirping shall be measured as well as the radiated power. 2) Demonstrate microsecond high power, high efficiency generation in Tomsk and shall conduct investigations of radiated frequency behavior during the pulse. The high-current accelerator, LUCH-2 will be used. Experts from US universities and industry who are part of the High Power Microwave MURI Project funded by AFOSR may participate in the testing at Tomsk.		
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## 1. INTRODUCTION.

At present, various relativistic microwave devices are applied for formation of microwave pulses of more than  $10^8$  W power. However, most of the known relativistic microwave generators have a considerable shortage. This shortage makes difficult to use these generators successfully. This shortage is a presence of additional magnetic systems with energy storage comparable to supply sources for formation of electron beams. It makes the radiation source installation more complex, large and heavy. Moreover, only part of energy of the supply source is used, because the known microwave generators operate efficiently at currents lower than vacuum limit currents. These currents lower than currents of energy sources by one-two orders. So, it leads to limitation of the radiation power and energy in the microwave pulse. It is necessary to note that resonant systems with transformation of electron flow energy to microwave oscillation energy have geometrical size comparable to the radiation wave length. It leads to limitation of power and energy of the microwave pulse due to microwave breakdown in the structure.

The generators with virtual cathodes (vircators) have no these limitations in application [1-3]. The microwave oscillations are generated in either region of the beam formation or near this region. It allows to reduce geometrical sizes of the generator. The vircators have oversize resonant systems. The electron beams can be formed without external magnetic fields. In the vircators, the generation takes place at currents higher than vacuum limit currents. One of the advantages of vircators is a tunable radiation frequency in wide frequency band [4]. Thus it is obvious that the vircator is one of the most perspective microwave generators. The vircator microwave generation can be divided into generation in nanosecond ( $t_p < 100$  ns) and microsecond ( $t_p > 100$  ns) bands. There are a lot of papers devoted to nanosecond microwave generation [5]. Number of papers devoted to microsecond generation is smaller considerably. However, increasing energy of the microwave pulse due to increasing of pulse duration is very important and interesting from the viewpoint of practical application. At the research of the vircator radiation generation in both nanosecond and microsecond band, the most actual question is the radiation frequency spectrum and efficiency of transformation of the beam energy to the energy of microwave radiation.

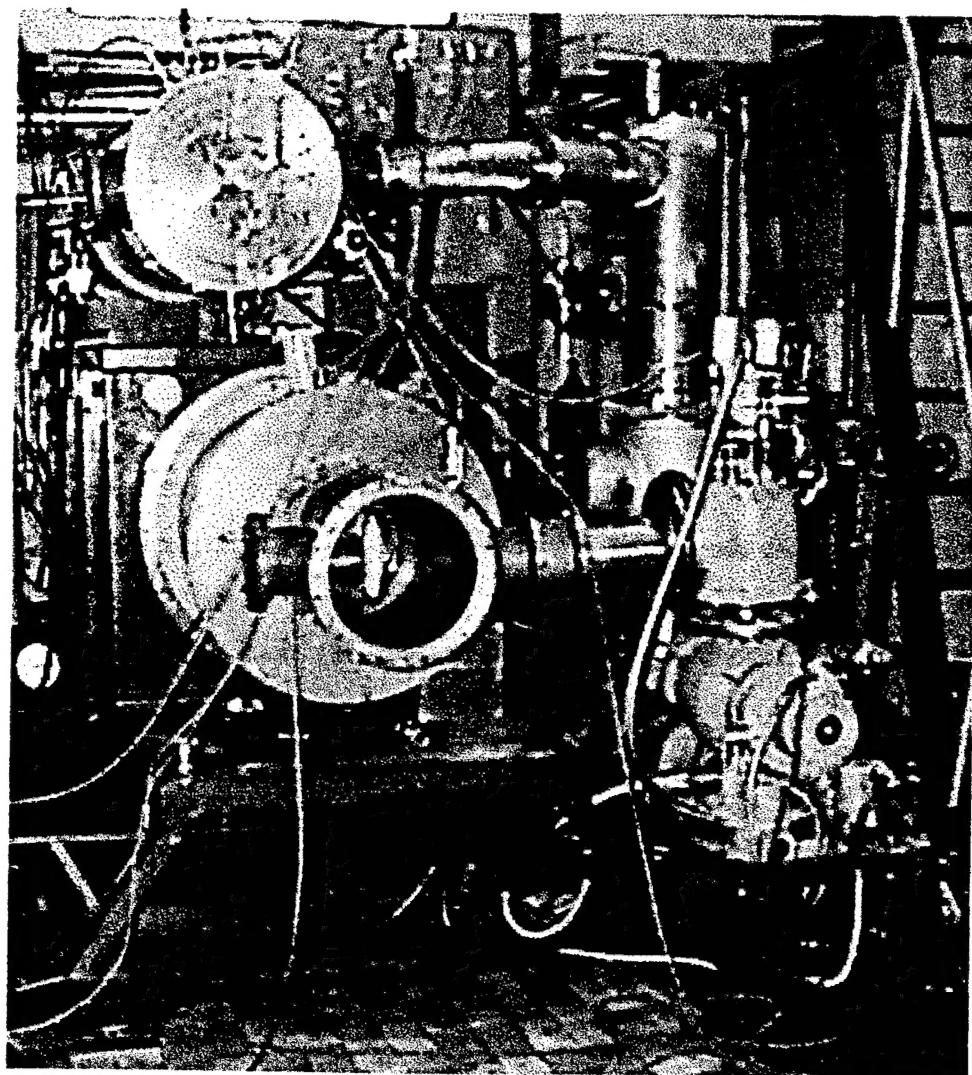
This work, developed in the frame of the contract, is devoted to solving these problems. The triode with virtual cathode has a specific place in a series of electron microwave devices, because processes of formation of high current electron flow, electron oscillations and transformation of flow energy to microwave radiation energy take place in the same electrodynamic structure. It influents to the generation process and efficiency, because the feedback between the resonator beam and the microwave field, excited in the triode, is the most effective in this case. The system has no passing particles, all electrons oscillate between real and virtual cathode. Presence of passing electrons reduce number of oscillating electrons and change radiation frequency spectrum [6]. As a result, comparing to other types of vircators, the efficiency of energy transformation in the triode with virtual cathode is higher considerably.

## 2. EXPERIMENTAL INSTALLATION.

It was shown in the preliminary report that the most convenient source for the vircator triode is a Marx high voltage source (capacitive storage). The pulse generator with following technical characteristics was developed and manufactured for production of high voltage microsecond pulses:

Storage energy	24 kJ;
«Shock» capacitance	33 nF;
Inductance	6 $\mu$ Hn;
Internal resistance	13 Ohm;
Output voltage at no-load	0.96 MV;
Pulse rise time on 30 Ohm load	120 ns;
Maximal sizes	1000 x 1000 x 2000 mm <sup>3</sup> .

The pulse generator is constructed on multiplying scheme on the basis of capacitors with 100 kV maximal voltage and 0.4  $\mu$ F capacity. It has 12 stages. The every stage consists of one capacitor. The generator stages are charged by the high voltage installation with maximal charging voltage of 80 kV and charging resistance of 2



*Fig. 1. Experimental installation.*

kOhm. The pulse generator stages are controlled by gas spark gaps, placed in insulated polyethylene tube. The generator starts by trigatron ignition of first spark gap. All elements of the generator are placed in steel tank of 2 m<sup>3</sup> volume, filled by transformer oil. Using transforming oil and steel closed tank allows reducing considerably inductance. The current return circuit (steel tank) can be manufactured more close to the spark gap circuit. The maximal strength of electric field in the transformer oil at action of microsecond voltage pulse is no higher than 60 kV/cm. This strength provides high insulation reliability of the construction. It is confirmed by many domestic and foreign high voltage installations. The last stage of the pulse generator is connected to high voltage input, consisted of a section insulator with an anode holder. The sections of the insulator are made of acrylic plastic. Number of sections is 10. The pulse voltage is distributed on the sections along the insulator by means of 100 Ohm resistances.

The measurement of charging and output voltage is carried out by active voltage dividers, whereas total current and vircator current - by Rogowsky coils. The vircator triode, consisted of the vacuum chamber with cathode and anode parts, is joint to output of the insulator. The construction of the vircator triode and devices required for evaluation of microwave radiation parameters are discussed in details in the preliminary report. At these parameters of the voltage source and the load (vircator triode), current and voltage have the same time dependence.

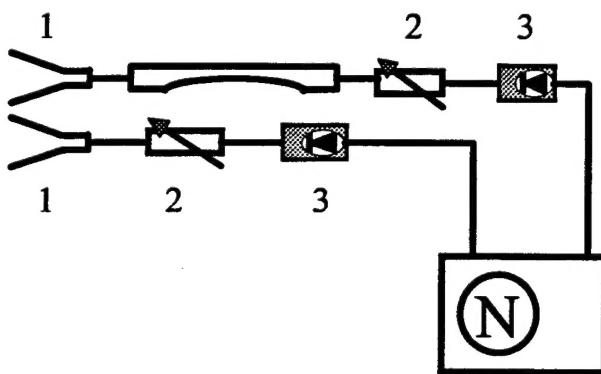
In order to produce nanosecond microwave pulses, the pulse generator is disconnected from the microsecond vircator triode and connected to a double forming line (DFL) with the nanosecond vircator. The DFL wave resistance is  $R=6.8$  Ohm, capacitance  $C=23,000$  pF. Resonant coefficient at the DFL charging from the pulse generator is  $k=1.5$ , whereas maximal voltage in the cathode-anode gap is  $\sim 750$  kV at pulse duration of  $t_p \sim 100$  ns.

### 3. RADIATION FREQUENCY MEASUREMENT

#### AND BEHAVIOR FOR THE PULSE TIME.

The radiation frequency, generated in the vircator triode, is determined considerably by voltage applied to the anode, and cathode-anode distance. For the microsecond regime of the vircator triode operation with application of high current accelerators, these characteristics are changed considerably. The explosion emission cathode, applied usually for these cases, forms plasma on the cathode surface. This plasma is a source of electron flow at the time of voltage pulse action. At the same time, this plasma moves to the anode. It leads to reduction of cathode-anode distance and cathode-anode impedance. It results in applied voltage changing. It is known that radiation frequency in the vircator triode is reverse proportional to the cathode-anode distance. When applied voltage is reduced, the radiation frequency is reduced. In the microsecond regime, both these processes take place simultaneously, i.e. reduction of the cathode-anode distance lead to the radiation frequency increasing, whereas reduction of applied voltage due to impedance reduction results in the radiation frequency reduction, the frequency is not expected to be changed considerably for the period of the microsecond pulse action.

In this work we measured frequency of the vircator triode for the pulse time by means of a tunable band filter and a series of high frequency filters on the basis of cut-off waveguides, according to the fig.2. This scheme includes two identical channels for measurements, consisted of receiving antennas 1, waveguide

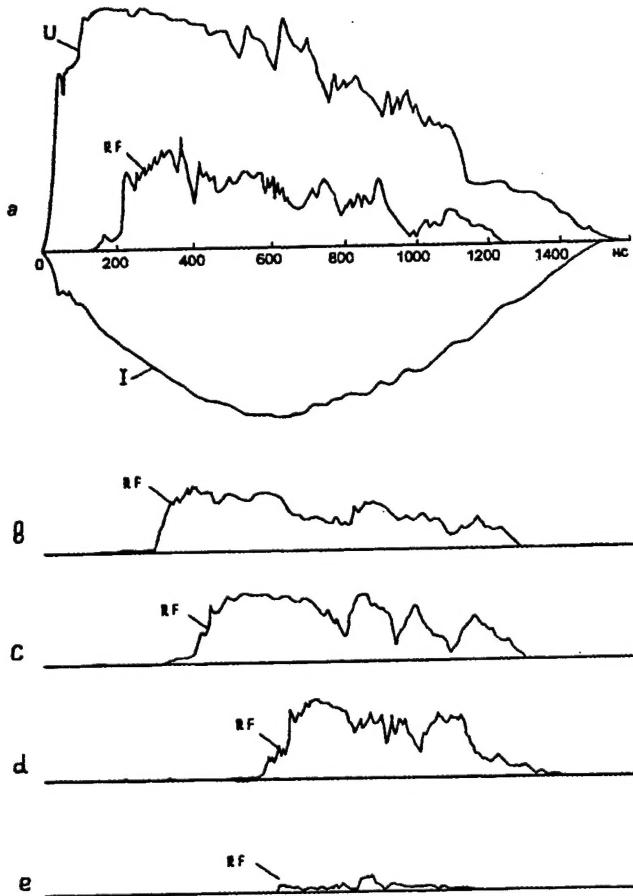


*Fig.2. Scheme of carrier frequency estimation by cut-off waveguides.*

attenuator 2 and detectors of microwave signals 3, connected to the signal registration N. In the one of the channels, high frequency filter or tunable band filter (in turn) are placed between receiving antenna 1 and waveguide attenuator 2. This channel serves

for registration of changes of the microwave pulse shape, taking place due to frequency filters. It allows evaluating the radiation frequency at the certain moment of time. The another channel does not changed. It serves for registration of real microwave pulse.

The fig. 3 presents typical oscillograms of the microwave pulses, measured on



*Fig. 3. Microwave radiation pulses, measured on the channels.*

the second channel (a), and pulses, measured on the first channel after high frequency filters with different critical frequencies. The fig. 3(b) shows the microwave radiation pulse shape after filter with critical frequency of 2.7 GHz. The fig. 3 (c) corresponds to the filter with critical frequency of 2.8 GHz, (d) - to 3.1 GHz, and (e) - to 3.5 GHz. In the high frequency filters, all electromagnetic waves with frequencies lower than the critical one are attenuated. The electromagnetic waves

with frequencies higher than 2.7 GHz can pass through the filter with critical frequency of 2.7 GHz only. This characteristics of waveguides is related to other high frequencies filters also and can be used for measurement of the microwave radiation frequency. Filters with lower critical frequencies do not influent to the shape of the real pulse. Hence start radiation frequency is between the critical frequency of the filter, which

<sup>ce</sup> influen~~ce~~ to the pulse shape, and critical frequency of the filter, which does not influence to the pulse shape. In our case, it is seen from the figure that the pulse rise time is reduced for the 2.7 GHz filter, whereas the pulse shape did not change for the 2.5 GHz filter. It means that the radiation frequency is from 2.5 GHz to 2.7 GHz from the start of the real pulse to the moment of the pulse appearance in the channel with the filter. Installation of the series of filters with higher critical frequencies increase pause time from the start of the real pulse to the moment of the pulse appearance in the channel with the filter while the signal did not appear at all (fig.3 (b,c,d,e)). Moreover, we carried out experiments, when tunable waveguide filter with 120 MHz bandwidth and tunable central frequency of the band was installed instead of high frequency filters. The radiation frequency characteristics had the same behavior as for case of cut-off waveguides.

The carried measurements of radiation frequency depending on time show that the generation in the vircator triode starts after 200-230 ns from the moment of voltage applying to the anode. The radiation frequency arises from ~2.5 GHz at start moment to 2.7 at 90-120 ns. Then, it arises up to 2.8 GHz at 120-140 ns. The radiation frequency from 2.8 GHz to 3.1 GHz corresponds to time from 500 ns to 710 ns. Then the radiation frequency is from 3.1 GHz to 3.3 GHz up to time, when the radiation power is not measurable (at 1.0-1.2  $\mu$ s). The radiation frequency higher than 3.3 GHz does not appear in this system. Thus, for the 1.5-2.0  $\mu$ s voltage pulse, the microwave radiation frequency of the vircator triode in microsecond regime is increased from ~2.5 GHz at the start moment to 3.3 GHz at the final moment of the generation of the 0.8-1.2  $\mu$ s microwave pulse.

#### 4. EFFICIENCY OF THE VIRCATOR TRIODE.

It was noted in preliminary report that the generation efficiency in the vircator triode is determined as the microwave radiation energy divided by the energy of electron flow for the generation period. The microwave radiation power is determined as integration of power flow on the radiation pattern at the certain moment of time. The radiation frequency is very important for determination of the power. It was shown in the upper part, the frequency of the microwave radiation has considerable

increase in the microsecond regime, and power level was considerably changed for the time of action of the voltage pulse.

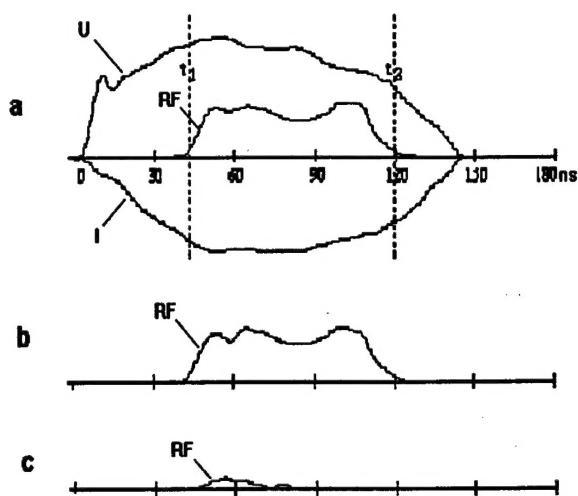
In these conditions, evaluation of efficiency of the vircator triode microwave generation in microsecond band by means of time integration of the microwave radiation is a very complex task. Any possible mistake at the calculation of the radiation power by this method is unallowable high. That is why the efficiency of the microwave radiation generation of the vircator triode for the microsecond regime was evaluated in the moment corresponding to maximal value of radiated power. Main results of carried experiments are presented in the Table. It is shown that for the microsecond regime, 6% efficiency of the microwave generation can be reached.

TABLE.

Parameter	Nanosecond Regime	Microsecond Regime
Triode Voltage, $U_{\max}$ , kV	570	370
Triode Current, $I_{\max}$ , kA	16	19
Voltage Pulse Duration at $0.1 U_{\max}$ , sec	$1.3 \cdot 10^{-7}$	$1.4 \cdot 10^{-6}$
Radiation Power, $P_{\max}$ , MW	700 - 800	350 - 450
Radiation Pulse Duration at $0.1 P_{\max}$ , sec	$8 \cdot 10^{-8}$	$8 \cdot 10^{-7}$
Maximal Efficiency, %	13	6
Average Efficiency for the Generation Time, %	8	-
Radiation Frequency, GHz	3.32	increase from 2.5 to 3.3
Radiation Spectrum Width, %	6	-

In order to study question of increasing efficiency of the microwave radiation generation in the vircator triode both for certain moment of time and for the generation time, we used direct electron accelerator on the basis of double forming line with ~120 ns pulse duration as a supply source of the vircator triode. In this case, the cathode plasma does not change considerably the cathode-anode distance. Thus, as measurements show (Table and fig.4) applied voltage and microwave radiation frequency are not changed considerably too. The maximal voltage applied to the anode

grid in this experiments was  $\sim 570$  kV. When the cathode-anode distance is equal to 19 mm, the maximal current in the triode reaches 16.5-17.0 kA, whereas the maximal level of the microwave radiation power was  $\sim 700$  MW. The fig.4(a) presents typical obtained oscillograms of voltage, current and microwave power. Both in



*Fig.4. Typical traces of vircator voltage, current and pulse microwave power*

the microsecond regime and in this case microwave radiation frequency was measured by means of a tunable band filter and a series of cut-off waveguides.

The fig.4(b) shows microwave radiation pulse shape after cut-off waveguides with critical frequency of 3.26 GHz, and (c) - to 3.5 GHz. The measurements carried by means of a tunable band filter

show that microwave radiation frequency is equal to 3.32 GHz in the nanosecond regime with spectrum width 6%. The microwave radiation energy was determined as time integration of the pulse microwave power from the moment  $t_1$  to the moment  $t_2$ . These moments correspond to time, when the level of the microwave power is equal to 0.1 of maximal level of the microwave power. The energy of the electron beam was determined as time integration of  $U(t)I(t)$  from  $t_1$  to  $t_2$ . The start of the microwave generation  $t_1$  delays from the voltage pulse start by about 40 ns. We consider this delay as time of the current appearance and rise up to the start level in the vircator triode. It was estimated that the generation efficiency was  $\sim 7.8\%$  (average efficiency). The efficiency of transformation of the electron flow energy to the microwave radiation energy in the vircator triode is changed depending on time. If estimated for 100 ns period, the generation efficiency is about 13.5% (maximal efficiency).

## 5. CONCLUSION.

The carried work show that the efficiency of the microwave generation can reach 13.5% at constant basic parameters (applied voltage, cathode-anode distance, radiation frequency, uniform electron flow).

Moreover, in the microsecond regime of the vircator triode operation in S-band, the radiation frequency arises from 2.5 GHz at the start moment of the generation to 3.3 GHz to the end of the generation. The total duration of the microwave pulse is 0.8-1.0  $\mu$ s. Even in this case, when the basic parameters are changed considerably, the efficiency of the vircator microwave generation reaches 6% at certain moments of time. The efficiency of the microwave generation, reached in the microsecond regime of the vircator operation, was obtained when the voltage and currents have the similar dependence on time. However, the carried experiments show preliminary that the triode can operate with more high efficiency, when the voltage source parameters are selected according to the condition of the current growth in the vircator triode for the period of the voltage pulse action.

The obtained results on research of the vircator triode microwave radiation generation show that a microwave radiation source with high efficiency can be developed on the basis of the vircator triode. This source can generate nanosecond and microsecond pulses in S-band.

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